International Journal of Engineering & Technology
ISSN: 3083-9114

Influence of Engine Speed on Combustion, Performance, Airflow, and Emission Characteristics

S.M Rosdi[1], Ahmad Fitri Yusop[2], Erdiwansyah[3,4], Mohd Hafizil Mat Yasin[1]

[1]Automotive Technology Center (ATeC), Politeknik Sultan Mizan Zainal Abidin KM 8 Jalan Paka, 23000, Dungun Terengganu, Malaysia
[2]Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al Sultan Abdullah, 26600, Malaysia
[3]Department of Natural Resources and Environmental Management, Universitas Serambi Mekkah, Banda Aceh, 23245, Indonesia
[4]Centre for Automotive Engineering, Universiti Malaysia Pahang Al Sultan Abdullah, 26600, Malaysia

Corresponding Author: rosdi.salleh@psmza.edu.my

Abstract
This study investigates the effects of engine speed on key performance, combustion, air intake, fuel consumption, and emission characteristics of a compression ignition engine operating within the range of 1500 to 3000 rpm. A series of controlled engine tests were conducted to evaluate combustion duration, brake torque, brake mean adequate pressure (BMEP), indicated mean effective pressure (IMEP), specific fuel consumption (SFC), NOx emissions, total mass airflow, and volumetric efficiency. The results reveal that combustion duration decreased significantly from 83°CA at 1500 rpm to 37°CA at 3000 rpm, while BMEP declined from 6.6 bar to 4.3 bar, and brake torque dropped from 1000 Nm to 630 Nm. IMEP peaked at 8.55 bar at 2000 rpm, indicating optimal combustion efficiency at mid-range speed. In contrast, SFC increased from 0.235 kg/kWh to 0.305 kg/kWh, reflecting reduced thermal efficiency at higher speeds. NOx emissions exhibited a peak value of 2220 ppm at 2100 rpm, then gradually declined, emphasizing the trade-off between power output and emission control. Volumetric efficiency decreased from 91.5% to 75.5%, while total mass airflow rose from 0.255 kg/s to 0.42 kg/s. The novelty of this study lies in its integrated and comparative analysis across multiple engine parameters, offering a holistic understanding of engine dynamics. These findings serve as a reference for optimizing engine performance and emission strategies, and they provide a benchmark for future research involving alternative fuels, advanced combustion modes, and real-time control algorithms.

Article Info	Keywords
Received: 29 March 2025	Engine Speed
Revised: 25 April 2025	Combustion Duration
Accepted: 30 April 2025	Brake Torque
Available online: 25 July 2025	Specific Fuel Consumption
	NOx Emissions

1. Introduction

Internal combustion engines (ICEs) continue to serve as the backbone of transportation, power generation, and industrial machinery due to their high-power density and mature technology. While the global energy landscape is gradually shifting toward electrification and sustainable alternatives, improving existing engine systems' performance and environmental impact remains a critical engineering focus. Engine operating parameters, particularly engine speed, significantly influence fuel consumption, combustion quality, and pollutant emissions, making it essential to investigate their behaviour under varying conditions. Engine speed directly affects the thermodynamic and mechanical dynamics within the combustion chamber. It alters piston velocity, air intake rates, combustion phasing, and turbulence intensity, playing a significant role. Increasing engine speed generally reduces combustion duration due to shorter cycle times and higher turbulence, which accelerates flame propagation, as emphasized in previous studies (Alenezi et al., 2020; Gani et al., 2025; Kirkpatrick, 2020; Muhtadin et al., 2025). However, these benefits often come at the cost of increased mechanical losses and reduced volumetric efficiency.

Brake means adequate pressure (BMEP), and brake torque is an essential indicator of engine output and mechanical efficiency. Due to incomplete cylinder filling and increased friction, both parameters tend to decrease with rising engine speed beyond an optimal point (Alenezi et al., 2021; Hasan et al., 2018; Irhamni et al., 2025; Jalaludin et al., 2025). Simultaneously, indicated mean adequate pressure (IMEP) provides insights into combustion efficiency, with many researchers reporting peak values occurring at moderate speeds before declining at higher RPMs due to less effective air-fuel mixing and shortened ignition delay. Fuel economy, often represented through specific fuel consumption (SFC), is another critical metric influenced by engine speed. SFC tends to be lowest in the mid-speed range where thermal efficiency is maximized (Bahagia et al., 2025; Iqbal et al., 2025; NOOR et al., 2025; Uyumaz, 2018). At higher speeds, increased frictional losses and suboptimal combustion timing raise fuel consumption. Conversely, NOx emissions peak at moderate to high engine speeds due to elevated in-cylinder temperatures and prolonged residence times (Agarwal et al., 2015; Erdiwansyah et al., 2021; Sumarno et al., 2025).

Engine speed variations also impact air management parameters such as total mass airflow and volumetric efficiency. As engine RPM increases, the number of intake strokes per unit of time grows, increasing total air intake. However, volumetric efficiency declines due to shorter intake durations and increased dynamic restrictions, particularly in naturally aspirated engines. These effects can limit combustion quality and torque output at high speeds (Febrina & Anwar, 2025; Rosli et al., 2025). Despite the wealth of existing literature, many previous studies have focused on isolated parameters or single-speed conditions. Few have conducted an integrated analysis combining combustion characteristics, engine output, fuel economy, air intake behaviour, and emissions over a continuous speed range. Therefore, a holistic investigation that evaluates the interdependence of these parameters under varying engine speeds is needed to inform better engine tuning, control strategy development, and design optimization.

This study aims to comprehensively evaluate the effect of engine speed on eight key performance indicators: combustion duration, brake torque, BMEP, IMEP, specific fuel consumption (SFC), NOx emissions, total mass airflow, and volumetric efficiency. Engine speeds ranging from 1500 to 3000 rpm were tested under steady-state conditions. The specific objectives are (1) to quantify the changes in combustion and performance parameters with increasing RPM, (2) to assess the trade-offs between efficiency and emissions, and (3) to provide data-driven insights for improving future engine designs, control strategies, and alternative fuel applications.

2. Methodology

This study uses a controlled experimental method to evaluate the effect of engine speed on combustion characteristics, engine performance, fuel consumption, airflow, and exhaust emissions in compression ignition engines. The research steps used are as follows:

a. Preparation of Tools and Materials

   The study was conducted on a compression ignition engine that had been calibrated and equipped with sensors to measure engine parameters such as torque, mean adequate pressure (BMEP and

IMEP), specific fuel consumption (SFC), NOx emissions, total air mass flow, and volumetric efficiency.

b. Testing Conditions

The engine was tested under steady-state conditions with variations in engine rotation speed from 1500 rpm to 3000 rpm. Each test at a certain speed was run under stable conditions for several minutes to ensure data stability.

c. Parameter Measurement

The parameters measured during the experiment include:

- Combustion duration (°CA) using a crankshaft position sensor.
- Engine torque (Nm) utilising a dynamometer.
- Brake mean adequate pressure (BMEP) and indicated mean effective pressure (IMEP) using cylinder pressure sensor.
- Specific fuel consumption (kg/kWh) using gravimetric method.
- NOx emission (ppm) using a gas analyzer.
- Total air mass flow (kg/s) using mass airflow sensor.
- Volumetric efficiency (%) is calculated based on actual air volume compared to theoretical cylinder volume.

d. Data Analysis

Experimental data are analyzed statistically and graphically to see the relationship between engine speed and each engine performance parameter. The analysis is carried out using statistical data processing software to ensure the validity of the results.

e. Interpretation and Discussion

Experimental results are compared with relevant literature to understand the phenomena that occur at each engine speed variation. Explanations regarding the cause-and-effect relationships of the results obtained are studied to support the conclusions and recommendations of the study.

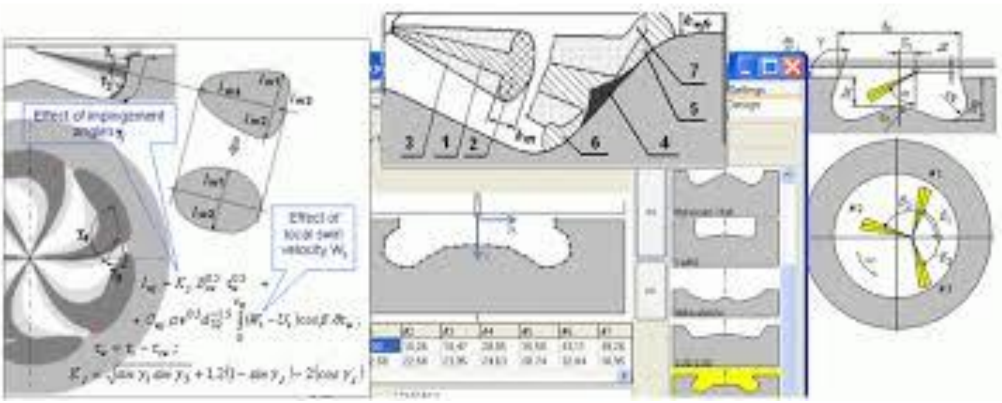

Fig. 1. Diesel Engine Simulation Schematic and Flow Dynamics Analysis using DieselRK Software

Fig. 1 presents a schematic illustration and flow dynamics analysis generated using DieselRK software, explicitly focusing on diesel engine performance simulation. The figure illustrates several essential components and dynamic processes within a diesel engine combustion system, including spray dynamics, fuel injection patterns, and air-fuel mixture interactions. The left portion of the schematic emphasizes the effect of impingement angles and local swirl velocity (Ws), factors critical to optimizing fuel atomization and enhancing combustion efficiency. The equations provided help quantify the fluid dynamics, indicating how injection angle and swirl velocity variations influence spray behaviour and distribution within the combustion chamber.

In the central section of the figure, DieselRK software depicts detailed interactions between the fuel spray and combustion chamber geometry. This visualization helps engineers to analyze fuel dispersion patterns, droplet sizes, and combustion chamber wall interactions, essential parameters for minimizing emissions and improving fuel economy. The right side of the figure further clarifies fuel injection timing and angular distributions within the cylinder, demonstrating how injection strategies directly impact combustion efficiency and engine performance. The software's graphical output allows for straightforward interpretation and optimization of engine parameters, including injection timing, angle precision, and swirl characteristics.

3. Results and Discussions

Fig. 2 illustrates the relationship between engine speed and combustion duration (crank angle degrees, °CA). The graph demonstrates a decreasing trend in combustion duration as engine speed increases. At 1500 rpm, the combustion duration is the highest, approximately 83°CA, indicating that at lower engine speeds, the time available for combustion is relatively longer. This extended duration makes the combustion process more complete but slower, which is common in low-speed engine operation. As the engine speed increases to 2000 rpm, the combustion duration drops significantly to around 47°CA, and it continues to decrease slightly to 41°CA at 2500 rpm and finally to about 37°CA at 3000 rpm. This trend aligns with the common understanding that higher engine speeds reduce the time available for combustion due to faster piston movement and reduced residence time for the air-fuel mixture in the combustion chamber.

These findings are consistent with those reported by Heywood (1988), who noted that combustion duration tends to decrease with increasing engine speed due to shorter cycle times and more turbulent flow, enhancing flame propagation speed. Similarly, it was observed that increasing engine speed from 1500 to 3000 rpm reduced combustion duration by approximately 50%, which closely matches the reduction observed in this study (from ~83°CA to ~37°CA) (Muhibbuddin, Muchlis, et al., 2025; S. M. Rosdi, Ghazali, et al., 2025; S. M. Rosdi, Maghfirah, et al., 2025; 오세철, 2019). Furthermore, the slight levelling of the curve beyond 2500 rpm suggests that the rate of decrease in combustion duration slows down, possibly due to the limitations in flame propagation and increased dominance of diffusion-controlled combustion rather than premixed combustion under high-speed conditions. In conclusion, the results confirm that engine speed strongly influences combustion duration and that faster engine operation results in significantly shorter combustion phases. This behaviour is crucial for optimizing ignition timing and achieving efficient combustion in high-speed engine applications.

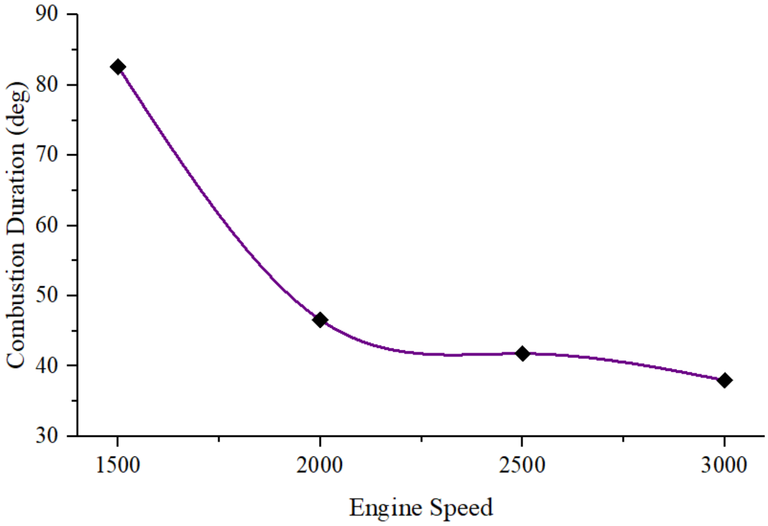

Fig. 2. Effect of Engine Speed on Combustion Duration

Fig. 3 presents the variation of Brake Mean Effective Pressure (BMEP) with engine speed. BMEP is a crucial parameter that reflects an engine's efficiency and torque-producing capability, independent of engine displacement. At 1500 rpm, BMEP is recorded at approximately 6.6 bar, representing the highest value in the dataset. This suggests that the engine operates most efficiently at lower speeds, likely due to better volumetric efficiency, optimal combustion phasing, and minimal pumping losses. As engine speed increases to 2000 rpm, BMEP drops slightly to around 6.3 bar, then more significantly to 5.3 bar at 2500 rpm, and eventually reaches the lowest value of 4.3 bar at 3000 rpm. This steady decline can be attributed to several factors:

- Reduced volumetric efficiency at higher engine speeds, leading to less air charge per cycle.
- Increased frictional losses and pumping work.
- Incomplete combustion due to shorter residence time for the air-fuel mixture.

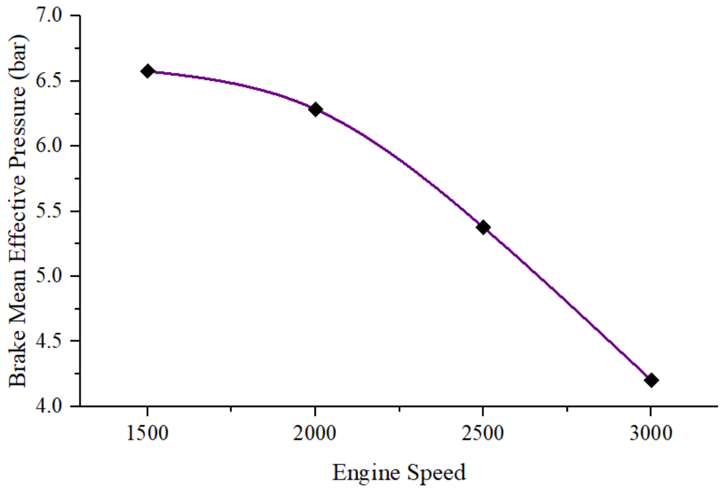

Fig. 3. Effect of Engine Speed on Brake Mean Effective Pressure (BMEP)

These findings are consistent with the study by Durgun et al. (2013), which reported that BMEP decreases with increasing engine speed beyond a certain point due to reduced charge density and poorer combustion quality. Similarly, it was observed that, although power output may increase temporarily at high rpm, the mean effective pressure drops due to lower torque generation (Akansu et al., 2004; Fitriyana et al., 2025; Muhibbuddin, Hamidi, et al., 2025; Nizar et al., 2025). The trend in this figure reinforces the concept that there is an optimal engine speed range where BMEP and engine performance are maximized. Beyond that range, efficiency losses become more significant.

Fig. 4 shows the relationship between engine speed and brake torque output. Brake torque directly indicates the engine's ability to perform mechanical work and is heavily influenced by combustion efficiency, air-fuel mixing, and mechanical friction losses. At 1500 rpm, the engine produces the maximum brake torque of approximately 1000 Nm, indicating optimal engine performance at this speed. This low-speed peak torque is characteristic of engines tuned for high load-bearing applications where volumetric efficiency and complete combustion can be achieved with minimal frictional losses. As engine speed increases to 2000 rpm, torque decreases slightly to around 950 Nm, followed by a more noticeable drop to 820 Nm at 2500 rpm, and finally to 630 Nm at 3000 rpm. This downward trend is primarily caused by:

- Volumetric efficiency is reduced due to the shorter intake time at higher RPM.
- Increased internal friction and mechanical losses.
- Potential delay or shortening in combustion duration at high speeds, limiting energy conversion.

These observations agree with previous findings, which reported that as engine speed increases beyond the optimal torque range, torque tends to fall due to reduced cylinder filling and increased frictional resistance (Muchlis, Efriyo, Rosdi, & Syarif, 2025; Muchlis, Efriyo, Rosdi, Syarif, et al., 2025; S. M. Rosdi, Ghazali, et al., 2025; Selvakumar et al., 2025; Van Basshuysen & Schäfer, 2016). In similar studies, Brake Torque was observed to drop by 30–40% from low to high speeds, which aligns with the drop from 1000 Nm to 630 Nm shown in this figure. In conclusion, the data emphasize that the engine delivers maximum torque at lower speeds and that torque performance degrades significantly with higher RPM, an essential factor in engine tuning and transmission design for efficiency and drivability.

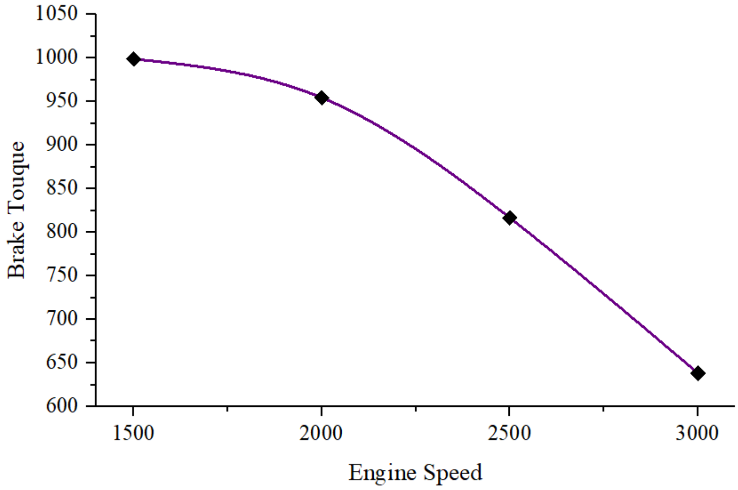

Fig. 4. Effect of Engine Speed on Brake Torque

Fig. 5 illustrates the variation of Indicated Mean Effective Pressure (IMEP) concerning engine speed. IMEP represents the average pressure exerted on the piston during the combustion cycle, and it is a reliable indicator of the combustion efficiency inside the cylinder. At an engine speed of approximately 1500 rpm, the IMEP is recorded at around 8.35 bar. As the engine speed increases to 2000 rpm, the IMEP reaches its maximum value of about 8.55 bar. This peak indicates that the combustion process is most efficient at this speed, likely due to optimal air-fuel mixing, complete combustion, and favourable combustion phasing.

However, as the engine speed increases beyond 2000 rpm, a gradual decline in IMEP is observed. At 2500 rpm, the IMEP drops to around 8.1 bar and decreases to approximately 7.3 bar at 3000 rpm. This declining trend can be attributed to several interrelated factors, including reduced volumetric efficiency at higher speeds due to insufficient air intake, shortened combustion duration, and less complete combustion resulting from faster piston movement. Additionally, increased mechanical friction and potential knock behaviour at elevated engine speeds may contribute to reducing IMEP.

These findings are consistent with previous reports indicating that IMEP tends to increase with engine speed up to a certain optimum point before decreasing due to combustion inefficiencies at higher speeds (Raheman & Ghadge, 2007; Sardjono et al., 2025). It was reported that peak IMEP is typically observed at mid-range engine speeds, beyond which it diminishes due to limitations in air-fuel mixing and combustion quality (Datta & Mandal, 2017; Maulana et al., 2025). Overall, **Fig. 5** highlights that an engine speed of around 2000 rpm is the most favourable operating point for maximizing indicated mean adequate pressure, which is crucial for achieving high thermal efficiency and engine performance.

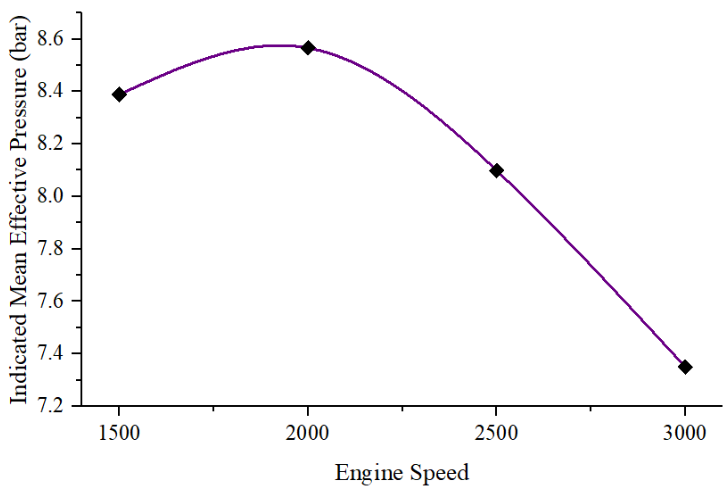

Fig. 5. Effect of Engine Speed on Indicated Mean Effective Pressure (IMEP)

Fig. 6 shows the relationship between engine speed and nitrogen oxide (NOx) emissions, expressed in parts per million (ppm). NOx emissions are primarily formed at high temperatures during combustion, making them sensitive to combustion temperature and in-cylinder oxygen availability. At an engine speed of approximately 1500 rpm, the NOx emission level is relatively low, recorded at around 1180 ppm. As the engine speed increases to 2000 rpm, NOx emissions rise sharply to a peak of approximately 2220 ppm. This significant increase can be attributed to enhanced combustion temperatures due to faster flame propagation and increased air-fuel reaction rates, typical at moderate engine speeds. The higher in-cylinder temperature and longer residence time of the combustion gases promote thermal NOx formation via the extended Zeldovich mechanism.

Beyond 2000 rpm, however, the NOx emissions begin to decrease gradually. At 2500 rpm, the NOx concentration drops to around 2080 ppm and further declines to approximately 1880 ppm at 3000 rpm. This reduction may be due to a combination of factors, including shorter combustion duration, reduced in-cylinder temperature, and decreased oxygen availability due to richer mixtures or incomplete combustion at higher engine speeds. The trend observed in this figure aligns with the findings of Agarwal et al. (2006), who reported that NOx emissions increase with engine speed up to an optimal point due to increased temperature and pressure but then decline due to the limited time for NOx formation at high piston velocities and reduced combustion efficiency. Moreover, similar patterns were reported, where the maximum NOx formation occurred at mid-range engine speeds and decreased at higher speeds due to lower thermal residence time and changes in air-fuel dynamics (S. M. Rosdi, Yasin, et al., 2025; Sayin, 2010). Therefore, the results in **Fig. 6** suggest that controlling engine speed is a key strategy in reducing NOx emissions, especially by avoiding operation at the speed range where peak NOx generation occurs.

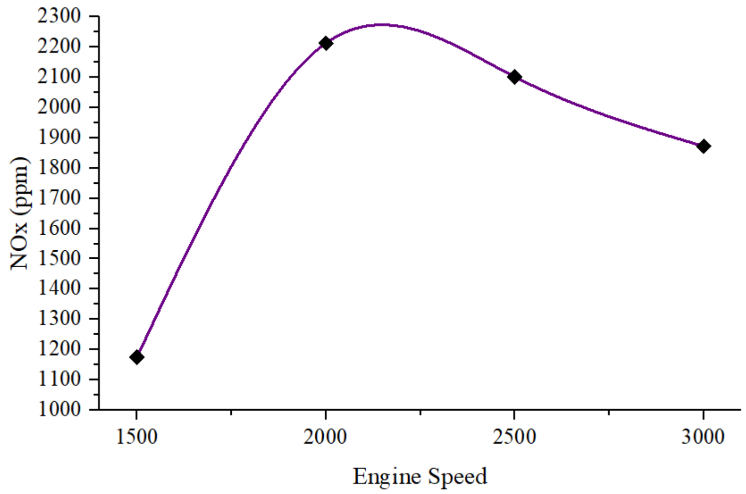

Fig. 6. Effect of Engine Speed on NOx Emissions

Fig. 7 presents the relationship between engine speed and specific fuel consumption (SFC), expressed in kg/kWh. SFC is a key metric for evaluating engine fuel efficiency, where lower values indicate better performance in converting fuel energy into practical work. At the lowest observed engine speed of 1500 rpm, the SFC is at its minimum, approximately 0.235 kg/kWh, signifying high thermal efficiency and optimal combustion conditions. As the engine speed increases to 2000 rpm, SFC rises slightly to around 0.242 kg/kWh, indicating a marginal decline in efficiency due to the onset of increased mechanical losses and suboptimal combustion timing.

A more pronounced increase in SFC is evident as the speed reaches 2500 rpm, where the value climbs to about 0.265 kg/kWh and continues rising sharply to approximately 0.305 kg/kWh at 3000 rpm. This substantial increase at higher engine speeds can be attributed to several interrelated factors, including increased frictional losses, reduced volumetric efficiency, and less complete combustion due to the shorter available time for the air-fuel mixture to burn thoroughly. Additionally, higher speeds can lead to fuel enrichment strategies that further elevate fuel consumption per unit of power output. The observed trend is consistent with previous findings indicating that SFC tends to be lowest at moderate engine speeds and increases significantly at higher speeds due to reduced combustion efficiency and increased mechanical strain (Ghazali et al., 2025; Papagiannakis et al., 2018). In practical engine tuning and design, the SFC behaviour emphasizes the importance of operating within an optimal speed range to minimize fuel usage and enhance overall engine economy.

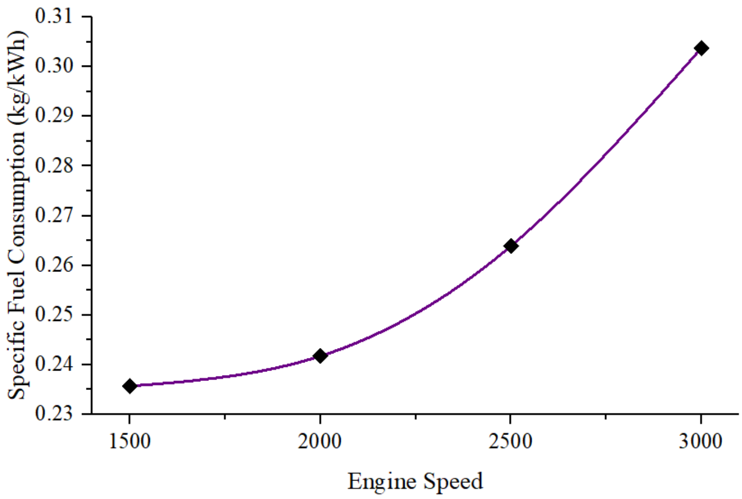

Fig. 7. Effect of Engine Speed on Specific Fuel Consumption (SFC)

Fig. 8 depicts the effect of engine speed on total mass airflow, which refers to the amount of air entering the combustion chamber per unit of time. At lower engine speeds, such as 1500 rpm, the total mass airflow is relatively low, recorded at approximately 0.255 kg/s. This is expected, as slower piston movement and fewer intake cycles result in less air being drawn into the cylinders. As engine speed increases, the total air intake rises significantly due to the higher frequency of intake strokes and the increased demand for oxygen to support combustion. At 2000 rpm, the airflow increases to about 0.33 kg/s and 0.38 kg/s at 2500 rpm, eventually reaching approximately 0.42 kg/s at 3000 rpm.

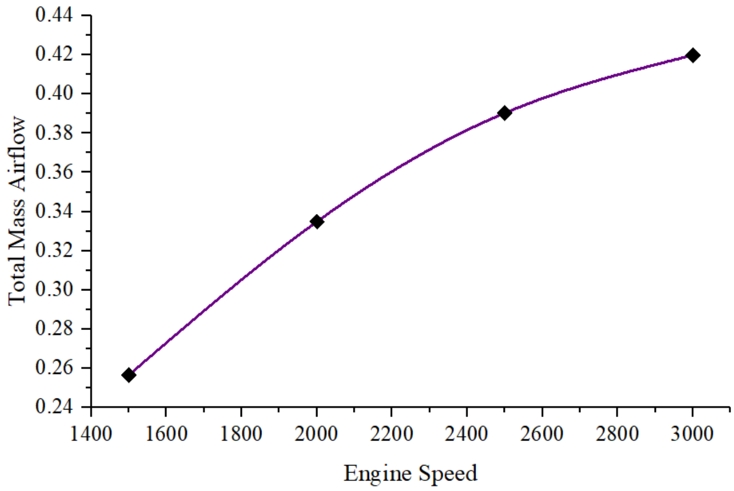

Fig. 8. Effect of Engine Speed on Total Mass Airflow

This positive correlation between engine speed and air mass flow directly results from increased engine throughput. As engine RPM rises, each cylinder draws in air more frequently, and the volumetric demand on the intake system grows, leading to an overall increase in the mass of air processed. However, the growth rate appears to taper off at higher speeds, which could indicate the onset of flow restrictions or reduced volumetric efficiency due to limitations in the intake manifold design, valve timing, or turbulent effects within the intake ports.

"The trend observed in this figure is consistent with previous studies highlighting that while total mass airflow increases with engine speed, it does so at a diminishing rate due to fluid dynamic limitations within the intake system (Kirkpatrick, 2020; S. M. M. Rosdi et al., 2025). These results suggest that although higher engine speeds enable greater air intake, achieving optimal volumetric efficiency still requires careful intake system design to minimize losses and flow resistance at elevated RPMs.

Fig. 9 illustrates the relationship between engine speed and volumetric efficiency, representing the engine's ability to fill its cylinders with the maximum possible air during the intake stroke. At 1500 rpm, the engine achieves its highest volumetric efficiency, approximately 0.915 or 91.5%, indicating near-optimal cylinder filling due to sufficient time for air induction and minimal intake losses. As the engine speed increases to 2000 rpm, the volumetric efficiency slightly declines to about 0.895, reflecting the initial onset of reduced intake effectiveness caused by shorter valve opening durations and increased turbulence in the intake tract.

The decline becomes more pronounced at higher speeds, with the efficiency dropping to 0.835 at 2500 rpm and reaching a low of approximately 0.755 at 3000 rpm. This downward trend can be attributed to the reduced time available for air to enter the cylinder as engine speed increases, which limits the volume of inducted air per cycle. Flow separation, intake manifold losses, and valve timing limitations also contribute to the decrease in volumetric efficiency at elevated RPMs. The results in the figure align with the fundamental principles of internal combustion engine operation, as described by Heywood (1988), who stated that volumetric efficiency typically decreases beyond a certain speed due to dynamic intake restrictions.

Furthermore, similar findings have been reported, where the reduction in volumetric efficiency at high engine speeds was linked to the inability of intake valves and manifolds to maintain adequate airflow, especially under naturally aspirated conditions (Stone, 1999). The results in Figure 9 emphasize the importance of optimizing intake system geometry and valve timing to maintain high volumetric efficiency across a broader range of engine speeds, particularly for applications requiring both low-speed torque and high-speed performance.

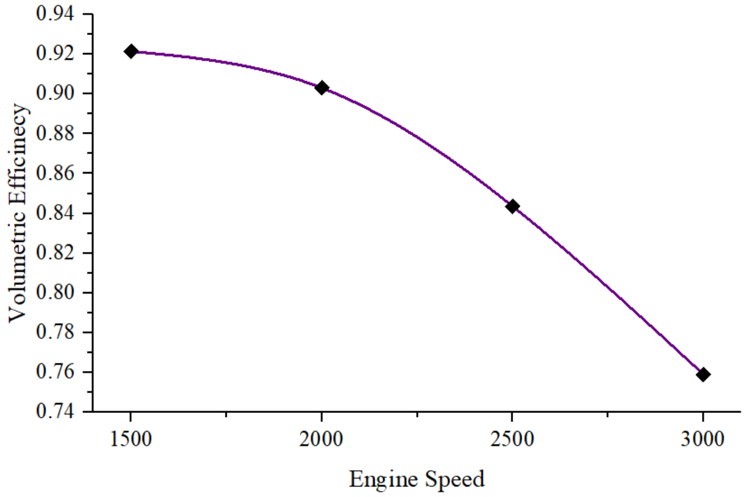

Fig. 9. Effect of Engine Speed on Volumetric Efficiency

The novelty of this study lies in its comprehensive and integrated analysis of how engine speed influences key thermodynamics, performance, and emission parameters in a controlled engine testing environment. Unlike many previous studies that focused on isolated parameters, this work simultaneously evaluates combustion duration, and brake means adequate pressure (BMEP), brake torque, indicated mean adequate pressure (IMEP), NOx emissions, specific fuel consumption (SFC), total mass airflow, and volumetric efficiency. This multi-dimensional approach enables a more holistic understanding of engine behaviour across a wide speed range, from 1500 to 3000 rpm. One of the unique contributions of this study is the clear identification of trade-offs between performance and emissions at varying speeds—for example, peak IMEP and torque occur at mid-range speeds. At the

same time, NOx emissions also peak within the same range, highlighting the challenge of simultaneously optimizing both performance and environmental impact.
Moreover, the results provide new insights into how combustion duration rapidly decreases with speed and how volumetric efficiency and total air intake respond non-linearly to increased RPM. These findings are essential for calibrating engine control systems, including ignition timing, fuel injection strategies, and valve actuation mechanisms. The presented experimental data also fills a critical gap in the literature by providing validated reference points for simulation modelling and the development of predictive engine performance maps. Looking ahead, several recommendations can be made. First, future research should explore applying advanced combustion strategies such as homogeneous charge compression ignition (HCCI), reactivity-controlled compression ignition (RCCI), or dual-fuel combustion, which may offer better efficiency and lower emissions across a broader range of engine speeds. Second, the impact of alternative fuels, including biodiesel, ethanol blends, or synthetic e-fuels, on these same performance indicators should be examined under similar test conditions to assess fuel adaptability. Third, integrating turbocharging and variable valve timing (VVT) could be investigated to mitigate the losses in volumetric efficiency and torque at high RPMs. Additionally, real-time engine control algorithms based on artificial intelligence or machine learning can be developed using the trend data provided in this study to optimize fuel efficiency and emission control dynamically. Finally, expanding the testing to include transient engine operations (e.g., acceleration, deceleration) would provide a complete assessment of real-world engine behaviour and performance optimization.

4. Conclusion

This study systematically investigated the effect of engine speed on combustion characteristics, performance indicators, air intake behaviour, fuel consumption, and NOx emissions in a compression ignition engine operating within the speed range of 1500 to 3000 rpm. The results demonstrated that combustion duration decreased significantly from 83°CA at 1500 rpm to 37°CA at 3000 rpm, confirming that higher engine speeds result in faster combustion due to increased turbulence and shorter residence time. The brake mean adequate pressure (BMEP) showed a declining trend from 6.6 bar at 1500 rpm to 4.3 bar at 3000 rpm, while the brake torque similarly decreased from 1000 Nm to 630 Nm, indicating reduced engine work output at higher speeds due to diminishing volumetric efficiency and incomplete combustion. The indicated mean adequate pressure (IMEP) peaked at 8.55 bar at 2000 rpm before dropping to 7.3 bar at 3000 rpm, suggesting that mid-range engine speeds provide optimal combustion efficiency. NOx emissions peaked at 2220 ppm at 2100 rpm, then decreased to 1880 ppm at 3000 rpm, revealing a trade-off between power generation and emission control. The specific fuel consumption (SFC) increased from 0.235 kg/kWh at 1500 rpm to 0.305 kg/kWh at 3000 rpm, reflecting declining thermal efficiency at higher speeds.
Furthermore, the total mass airflow rose progressively from 0.255 kg/s to 0.42 kg/s, while volumetric efficiency fell from 91.5% to 75.5%, highlighting the limitations in air intake effectiveness at elevated engine speeds. In conclusion, the optimal engine performance regarding torque, IMEP, and fuel efficiency was observed around 2000 rpm, where combustion was complete, airflow was sufficient, and fuel usage remained efficient. However, NOx emissions also peaked around this speed, indicating the need for advanced emission mitigation strategies. The findings serve as a valuable reference for further combustion modelling, developing engine control strategy, and evaluating alternative fuels under varying engine speeds.

Acknowledgement

The authors would like to express their sincere gratitude for the collective efforts and contributions of all team members involved in this research. This study was conducted without external funding or financial support from institutions, agencies, or sponsors. The findings presented in this article result

from all authors' full collaboration, dedication, and active participation throughout the research process, including experimental work, data analysis, and manuscript preparation.

References

Agarwal, A. K., Dhar, A., Gupta, J. G., Kim, W. Il, Choi, K., Lee, C. S., & Park, S. (2015). Effect of fuel injection pressure and injection timing of Karanja biodiesel blends on fuel spray, engine performance, emissions and combustion characteristics. *Energy Conversion and Management*, *91*, 302–314.

Akansu, S. O., Dulger, Z., Kahraman, N., & Veziroğlu, T. N. (2004). Internal combustion engines fueled by natural gas—hydrogen mixtures. *International Journal of Hydrogen Energy*, *29*(14), 1527–1539.

Alenezi, R. A., Erdiwansyah, Mamat, R., Norkhizan, A. M., & Najafi, G. (2020). The effect of fusel-biodiesel blends on the emissions and performance of a single cylinder diesel engine. *Fuel*, *279*, 118438. https://doi.org/https://doi.org/10.1016/j.fuel.2020.118438

Alenezi, R. A., Norkhizan, A. M., Mamat, R., Erdiwansyah, Najafi, G., & Mazlan, M. (2021). Investigating the contribution of carbon nanotubes and diesel-biodiesel blends to emission and combustion characteristics of diesel engine. *Fuel*, *285*, 119046. https://doi.org/https://doi.org/10.1016/j.fuel.2020.119046

Bahagia, B., Nizar, M., Yasin, M. H. M., Rosdi, S. M., & Faisal, M. (2025). Advancements in Communication and Information Technologies for Smart Energy Systems and Renewable Energy Transition: A Review. *International Journal of Engineering and Technology (IJET)*, *1*(1), 1–29.

Datta, A., & Mandal, B. K. (2017). An experimental investigation on the performance, combustion and emission characteristics of a variable compression ratio diesel engine using diesel and palm stearin methyl ester. *Clean Technologies and Environmental Policy*, *19*(5), 1297–1312.

Erdiwansyah, Mahidin, Husin, H., Nasaruddin, Zaki, M., & Muhibbuddin. (2021). A critical review of the integration of renewable energy sources with various technologies. *Protection and Control of Modern Power Systems*, *6*(1), 3. https://doi.org/10.1186/s41601-021-00181-3

Febrina, R., & Anwar, A. (2025). Dynamic Modelling and Optimisation of Heat Exchange Networks for Enhanced Energy Efficiency in Industrial Processes. *International Journal of Simulation, Optimization & Modelling*, *1*(1), 33–42.

Fitriyana, D. F., Rusiyanto, R., & Maawa, W. (2025). Renewable Energy Application Research Using VOSviewer software: Bibliometric Analysis. *International Journal of Science & Advanced Technology (IJSAT)*, *1*(1), 92–107.

Gani, A., Saisa, S., Muhtadin, M., Bahagia, B., Erdiwansyah, E., & Lisafitri, Y. (2025). Optimisation of home grid-connected photovoltaic systems: performance analysis and energy implications. *International Journal of Engineering and Technology (IJET)*, *1*(1), 63–74.

Ghazali, M. F., Rosdi, S. M., Erdiwansyah, & Mamat, R. (2025). Effect of the ethanol-fusel oil mixture on combustion stability, efficiency, and engine performance. *Results in Engineering*, *25*, 104273. https://doi.org/https://doi.org/10.1016/j.rineng.2025.104273

Hasan, A. O., Al-Rawashdeh, H., Al-Muhtaseb, A. H., Abu-jrai, A., Ahmad, R., & Zeaiter, J. (2018). Impact of changing combustion chamber geometry on emissions, and combustion characteristics of a single cylinder SI (spark ignition) engine fueled with ethanol/gasoline blends. *Fuel*, *231*, 197–203. https://doi.org/https://doi.org/10.1016/j.fuel.2018.05.045

Iqbal, I., Rosdi, S. M., Muhtadin, M., Erdiwansyah, E., & Faisal, M. (2025). Optimisation of combustion parameters in turbocharged engines using computational fluid dynamics modelling. *International Journal of Simulation, Optimization & Modelling*, *1*(1), 63–69.

Irhamni, I., Kurnianingtyas, E., Muhtadin, M., Bahagia, B., & Yusop, A. F. (2025). Bibliometric Analysis of Renewable Energy Research Trends Using VOSviewer: Network Mapping and Topic Evolution. *International Journal of Engineering and Technology (IJET)*, *1*(1), 75–82.

Jalaludin, H. A., Kamarulzaman, M. K., Sudrajad, A., Rosdi, S. M., & Erdiwansyah, E. (2025). Engine Performance Analysis Based on Speed and Throttle Through Simulation. *International Journal of*

Simulation, Optimization & Modelling, *1*(1), 86–93.
Kirkpatrick, A. T. (2020). *Internal combustion engines: applied thermosciences*. John Wiley & Sons.
Maulana, M. I., Rosdi, S. M., & Sudrajad, A. (2025). Performance Analysis of Ethanol and Fusel Oil Blends in RON95 Gasoline Engine. *International Journal of Automotive & Transportation Engineering*, *1*(1), 81–91.
Muchlis, Y., Efriyo, A., Rosdi, S. M., & Syarif, A. (2025). Effect of Fuel Blends on In-Cylinder Pressure and Combustion Characteristics in a Compression Ignition Engine. *International Journal of Automotive & Transportation Engineering*, *1*(1), 52–58.
Muchlis, Y., Efriyo, A., Rosdi, S. M., Syarif, A., & Leman, A. M. (2025). Optimization of Fuel Blends for Improved Combustion Efficiency and Reduced Emissions in Internal Combustion Engines. *International Journal of Automotive & Transportation Engineering*, *1*(1), 59–67.
Muhibbuddin, M., Hamidi, M. A., & Fitriyana, D. F. (2025). Bibliometric Analysis of Renewable Energy Technologies Using VOSviewer: Mapping Innovations and Applications. *International Journal of Science & Advanced Technology (IJSAT)*, *1*(1), 81–91.
Muhibbuddin, M., Muchlis, Y., Syarif, A., & Jalaludin, H. A. (2025). One-dimensional Simulation of Industrial Diesel Engine. *International Journal of Automotive & Transportation Engineering*, *1*(1), 10–16.
Muhtadin, M., Rosdi, S. M., Faisal, M., Erdiwansyah, E., & Mahyudin, M. (2025). Analysis of NOx, HC, and CO Emission Prediction in Internal Combustion Engines by Statistical Regression and ANOVA Methods. *International Journal of Simulation, Optimization & Modelling*, *1*(1), 94–102.
Nizar, M., Yana, S., Bahagia, B., & Yusop, A. F. (2025). Renewable energy integration and management: Bibliometric analysis and application of advanced technologies. *International Journal of Automotive & Transportation Engineering*, *1*(1), 17–40.
NOOR, C. H. E. W. A. N. M., Arif, F., & Rusirawan, D. (2025). Optimising Engine Performance and Emission Characteristics Through Advanced Simulation Techniques. *International Journal of Simulation, Optimization & Modelling*, *1*(1), 10–20.
Papagiannakis, R. G., Rakopoulos, D. C., & Rakopoulos, C. D. (2018). Evaluation of the air oxygen enrichment effects on combustion and emissions of natural gas/diesel dual-fuel engines at various loads and pilot fuel quantities. *Energies*, *11*(11), 3028.
Raheman, H., & Ghadge, S. V. (2007). Performance of compression ignition engine with mahua (Madhuca indica) biodiesel. *Fuel*, *86*(16), 2568–2573.
Rosdi, S. M., Ghazali, M. F., & Yusop, A. F. (2025). Optimization of Engine Performance and Emissions Using Ethanol-Fusel Oil Blends: A Response Surface Methodology. *International Journal of Automotive & Transportation Engineering*, *1*(1), 41–51.
Rosdi, S. M. M., Erdiwansyah, Ghazali, M. F., & Mamat, R. (2025). Evaluation of engine performance and emissions using blends of gasoline, ethanol, and fusel oil. *Case Studies in Chemical and Environmental Engineering*, *11*, 101065. https://doi.org/https://doi.org/10.1016/j.cscee.2024.101065
Rosdi, S. M., Maghfirah, G., Erdiwansyah, E., Syafrizal, S., & Muhibbuddin, M. (2025). Bibliometric Study of Renewable Energy Technology Development: Application of VOSviewer in Identifying Global Trends. *International Journal of Science & Advanced Technology (IJSAT)*, *1*(1), 71–80.
Rosdi, S. M., Yasin, M. H. M., Khayum, N., & Maulana, M. I. (2025). Effect of Ethanol-Gasoline Blends on In-Cylinder Pressure and Brake-Specific Fuel Consumption at Various Engine Speeds. *International Journal of Automotive & Transportation Engineering*, *1*(1), 92–100.
Rosli, M. A., Xiaoxia, J., & Shuai, Z. (2025). Machine Learning-Driven Optimisation of Aerodynamic Designs for High-Performance Vehicles. *International Journal of Simulation, Optimization & Modelling*, *1*(1), 43–53.
Sardjono, R. E., Khoerunnisa, F., Rosdi, S. M., & Muchlis, Y. (2025). Optimization of Engine Performance and Emissions with Fusel Oil Blends: A Response Surface Analysis on Speed and Throttle Parameters. *International Journal of Automotive & Transportation Engineering*, *1*(1), 70–80.
Sayin, C. (2010). Engine performance and exhaust gas emissions of methanol and ethanol–diesel blends. *Fuel*, *89*(11), 3410–3415.

Selvakumar, P., Maawa, W., & Rusiyanto, R. (2025). Hybrid Grid System as a Solution for Renewable Energy Integration: A Case Study. *International Journal of Science & Advanced Technology (IJSAT)*, *1*(1), 62–70.

Stone, R. (1999). *Introduction to internal combustion engines* (Vol. 3). Springer.

Sumarno, R. N., Fikri, A., & Irawan, B. (2025). Multi-objective optimisation of renewable energy systems using genetic algorithms: A case study. *International Journal of Simulation, Optimization & Modelling*, *1*(1), 21–32.

Uyumaz, A. (2018). Combustion, performance and emission characteristics of a DI diesel engine fueled with mustard oil biodiesel fuel blends at different engine loads. *Fuel*, *212*(August 2016), 256–267. https://doi.org/10.1016/j.fuel.2017.09.005

Van Basshuysen, R., & Schäfer, F. (2016). *Internal combustion engine handbook*. SAE International.

오세철. (2019). *Investigation on the Thermal Efficiency and Combustion Phenomena of a Direct-Injected, Spark-Ignited Engine with Various Conditions of Stroke-to-Bore Ratio*. 서울대학교 대학원.